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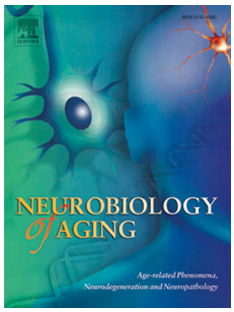

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Different trajectories of decline for global form and global motion processing in ageing, Mild Cognitive Impairment and Alzheimer's disease

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Abstract

The visual processing of complex motion is impaired in Alzheimer's disease (AD). However, it is unclear whether these impairments are biased towards the motion stream or part of a general disruption of global visual processing, given some reports of impaired static form processing in AD. Here, for the first time, we directly compared the relative preservation of motion and form systems in AD, Mild Cognitive Impairment (MCI) and healthy ageing, by measuring coherence thresholds for well-established global rotational motion and static form stimuli known to be of equivalent complexity. Our data confirm a marked motion-processing deficit specific to some AD patients, and greater than any form-processing deficit for this group. In parallel, we identified a more gradual decline in static form recognition, with thresholds raised in MCI patients and slightly further in the AD group compared with controls. We conclude that complex motion processing is more vulnerable to decline in dementia than complex form processing, perhaps owing to greater reliance on long-range neural connections heavily targeted by AD pathology.

1. Introduction

Motion and form appear to be analysed in different cortical systems, often equated to the dorsal and ventral processing streams respectively (Ungerleider & Mishkin, 1982; Milner & Goodale, 1995). Evidence suggests that global motion processing systems are slower to develop and more vulnerable to disruption than those for processing static form (Gunn et al, 2002). For example, in a variety of developmental disorders, motion coherence thresholds are more affected than form coherence thresholds (e.g. Spencer et al, 2000; Braddick et al, 2016), indicating that for these children, the ability to detect coherent motion in noise is much more impaired than the detection of equivalent static form in noise. This has led to the idea of "dorsal stream vulnerability" in infancy and childhood (Braddick et al, 2003).

It is unclear whether or not motion processing systems remain preferentially prone to deterioration in older adults. In support of such an idea are data showing that patients with Alzheimer's disease (AD) have marked difficulties in many complex motion processing tasks (e.g. Rizzo & Nawrot, 1998; Mapstone et al, 2008), together with a growing number of studies reporting specific motion processing deficits in healthy older compared with younger adults (see review by Hutchinson et al, 2012). However, recent evidence has also demonstrated age-related impairments of aspects of global form processing (e.g. Roudaia et al, 2011; McKendrick, Weymouth & Battista, 2013), and likewise AD patients have been reported to have difficulties with form-related tasks (Kurylo et al, 2003; Uhlhaas et al, 2008). It is possible, therefore, that age- and AD-related declines occur broadly across global visual processing mechanisms, rather than being motion-specific. In this study, our aim was to give a clean and simple overview of the relative preservation of global motion and form processing systems in healthy ageing, mild cognitive impairment (MCI) and AD, using well established motion and form coherence stimuli of equivalent complexity (Atkinson et al, 1997; Atkinson & Braddick, 2005).

Motion and form in Alzheimer's disease

There is now considerable evidence for deficits at complex motion-processing tasks in AD patients. People with AD are less able than healthy controls to identify shape from motion (Rizzo & Nawrot, 1998; Rizzo et al, 2000; Kim 2012), to discriminate optic flow (Tetewsky & Duffy, 1999; Mapstone et al, 2008, Kavcic et al 2011) and to process objects moving incongruently with their own apparent motion (Mapstone & Duffy, 2010). Imaging with fMRI shows less activation of motion-processing areas in AD patients than controls when viewing moving 3D stimuli (Thiyagesh et al, 2009), and with EEG, a reduced amplitude of response to motion onset (Kubová et al, 2010) or changing optic flow stimuli (Fernandez & Duffy, 2012; Fernandez et al, 2013). Nevertheless, patients' performance of simple motion-related tasks such as discriminating the direction of horizontal motion is typically more comparable to healthy controls' (Rizzo & Nawrot, 1998; Tetewsky & Duffy, 1999; Rizzo et al 2000; Mapstone et al, 2008). Many reports demonstrate much greater vulnerability to AD pathology in the long cortico-cortical projections of visual association cortex rather than in primary visual cortex (Lewis et al, 1987; Hof and Morrison, 1990; McKee et al, 2006; Beker et al, 2012; Carlyle et al, 2014), perhaps leading to more disrupted global than local processing (Beker et al, 2012). Taken together, these patterns suggest that lower level/local motion processing systems may be relatively preserved in AD, while higher level/global motion systems suffer more damage.

Fewer studies have specifically examined form processing in AD, despite AD patients having been indicated to have difficulties with visual grouping (Kurylo et al, 2003) and static

contour integration tasks (Uhlhaas et al, 2008). In both of these studies, deficits varied between individuals and those with occipital pathology struggled most (Uhlhaas et al, 2008), but whether this implies primarily lower level damage which might also have impaired motion processing was not tested. Some studies have attempted to compare dorsal and ventral stream processing in dementia, with mixed results. Velarde et al (2012) found independently raised thresholds for both motion discrimination and text discrimination in AD, suggesting damage to both streams. Other reports tend to emphasise supposedly dorsal stream deficits over those associated with the ventral stream. Nguyen, Chubb & Huff (2003) found AD patients to be disrupted at recognising stimulus location but not stimulus identity, suggesting dorsal-specific deficits, although their data were probably insensitive to more subtle form-based difficulties. Bokde et al (2010) used fMRI to show that, compared with controls, AD patients recruit additional brain areas when performing location-matching but not face-matching tasks. Similarly, Kubová et al (2010) and Sartucci et al (2010) report a reduced amplitude of EEG response in AD patients versus controls to radial optic flow, and high contrast luminance gratings reversed at high temporal frequency ("dorsal stream"), but not stimuli thought to represent ventral stream processing. Overall, while form-based impairments may occur in AD, the evidence is of lesser magnitude and consistency than the evidence for decline in motion systems.

Motion and form in healthy ageing

In direct contrast to the pattern for AD patients, evidence suggests that in healthy older adults lower level motion processing mechanisms are those most likely to suffer some disruption. For example, sensitivities for simple horizontal translational motion may be tuned to a narrower range of stimulus speeds as age increases (Atchley & Andersen, 1998; Snowden & Kavanagh 2006; Billino, Bremmer & Gegenfurtner, 2008; Allen et al, 2010; Arena, Hutchinson & Shimozaki, 2012). The processing of more complex motion signals, though, may not necessarily show age-related deficits. Billino et al (2008) report that judgements of radial optic flow were unimpaired, and of biological motion only slightly impaired with ageing, suggesting selective preservation of the most ecologically relevant motion systems (see Atchley & Andersen, 1998 and Allen et al, 2010, for similar patterns). In normal ageing, then, despite some lower level declines, there may perhaps be capacity for top-down compensation by higher level motion mechanisms in more complex tasks (Billino et al, 2008; Roudaia et al, 2010), although not all reports agree (e.g. Kavcic, Vaugn & Duffy, 2011).

The lower level contributors to age-related motion deficits seem to include an age-impaired ability to integrate spatial information (e.g. across larger displacements of dots between frames), at least as much as problems with integrating temporal information (e.g. across larger inter-stimulus intervals, or less frequent occlusion events) (Andersen & Ni, 2008; Roudaia et al, 2010; Arena et al, 2012). Since the spatial integration of local elements is also crucial to global form judgements (Aspell, Wattam-Bell, & Braddick, 2006), it is unsurprising that recent work has demonstrated some differences between young and old on many contour integration and shape perception tasks, especially with dense distractors (Del Viva & Agostini, 2007; Roudaia et al 2008, 2011, 2013; Weymouth & McKendrick 2012; McKendrick et al, 2010; 2013). Alongside these lower level changes in form processing is some evidence for preserved performance at higher level form tasks across the lifespan, such as perceptual learning of contour discrimination (McKendrick & Battista, 2013; see also Hadad, 2012), although the strategies and neural circuits involved may change with age (Kuai & Kourtzi, 2013; Mayhew & Kourtzi, 2013). The overall patterns of age-related change therefore seem broadly similar for form and motion systems, although little evidence directly compares the two, other than more prolonged motion onset (dorsal) visual evoked potential

(VEP) latencies than pattern reversal (ventral) (Kuba et al, 2012). The relative preservation of the two streams in normal ageing remains a largely open question.

Motion and form in Mild Cognitive Impairment

Patients with a diagnosis of MCI represent a mixed group, some destined to deteriorate further to dementia, and others with less severe prognosis, who may remain stable or even return to full health. Amnestic MCI (aMCI) is especially likely to progress to AD. Studying MCI is important because being able to identify the early-AD sub-group amongst them may allow earlier diagnosis and treatment (Sperling et al, 2011). Nevertheless, few reports examine MCI patients' motion or form processing capabilities, and there are mixed findings in keeping with the heterogeneous nature of MCI groups. Yamasaki et al (2012a and b) showed delayed EEG responses and reduced fMRI activation to optic flow in MCI versus healthy ageing, suggesting higher level motion deficits, and similarly Lemos et al (2012) claim selective decline of higher level dorsal stream function in aMCI, although using a shape-from-motion task for which the neural correlates were untested. Both of these results are similar to the overall reporting patterns for AD, suggesting early deterioration of motion-specific systems in MCI. However, fMRI evidence also points at ventral stream changes in MCI, both using face processing tasks (Bokde et al, 2006; Graewe et al, 2013), and in activation patterns during location matching (Bokde et al 2008). MCI may therefore involve more general or widespread brain changes than would fit within a simple dorsal stream decline model, perhaps depending upon the extent to which early-AD versus other causes is represented within an MCI sample.

Comparing motion and form processing

None of the previous studies which have attempted to compare motion and form processing in these older groups has used stimuli which facilitate direct comparison. Typically, tasks or stimuli are tailored to preferentially activate one or other processing stream rather than to be equivalent across streams (e.g. Lemos et al, 2003; Velarde et al, 2012). The data analysed for each may be of quite different format (Lemos et al, 2003), from different EEG waveforms (Kubova et al, 2010, Kuba et al, 2012), or uncalibrated in terms of task difficulty (e.g. Nguyen et al, 2003; Velarde et al, 2012). A such, they favour comparisons between groups within a stream, rather than across streams (see also Graewe et al, 2013), making it difficult to assess whether apparently more marked deficits in motion than form processing may arise because motion tasks typically challenge global visual processing mechanisms more severely than form-processing tasks, which are often less complex. The coherence stimuli used in the present study, however, were specifically designed to be of equivalent complexity for motion and form in healthy adults. They have been tested over many years and demonstrated to activate close but anatomically distinct neural pathways within extrastriate, parietal and temporal cortex (Braddick et al, 2000), compatible with evolving ideas of the interconnected networks involved in classic "dorsal" and "ventral stream" visual processing (e.g. de Haan & Cowey, 2011). The two tasks can be performed even by young children (Atkinson et al, 1997; Gunn et al, 2002; Atkinson & Braddick, 2005; Braddick et al, in press), and yield clean, unambiguous data in the form of a single index of performance for each participant – directly comparable across tasks. Thus, the stimuli used here are ideally suited to evaluating the relative preservation of equivalent motion and form processing systems in older adults who may show declining cognitive function.

Summary

In summary, here we measured coherence thresholds for young adults, healthy older adults, aMCI patients and AD patients using rotational motion and concentric form stimuli, in order

to gauge the relative preservation of global motion and global form processing systems in cognitively healthy and pathological ageing. Importantly, our two tasks have been heavily tested and demonstrated to be of equivalent difficulty in healthy adults, with performance involving anatomically separate cortical pathways (Braddick et al, 2000). Previous reports lead us to expect well preserved performance at this complex motion task in healthy ageing, but a decline in AD and perhaps also aMCI. For the comparable form task, we hypothesised a similar pattern but with less severe deficits in the patient groups.

2. Method

2.1 Participants

Twenty eight patients (16 male) with a recent clinical diagnosis of probable AD according to current guidelines (*DSM-IV* and *NINDS–ADRDA*) criteria (McKhann et al 1984) were recruited from Cardiff (n=16) and Bristol (n=12) memory clinics. Half (n=14) were stable on cholinesterase treatment at the time of testing while the remainder were not taking any medication likely to affect cognitive functioning. Ages ranged from 58 to 90 (mean 75.9, SD 7.85) years. Scores on the mini-mental state examination (MMSE) were between 16 and 26 (mean 22.3, SD 2.82), indicating mild to moderate severity of dementia. The mean pre-morbid IQ estimated by the National Adult Reading Test (NART) was 109.7 (SD 10.5), and estimated by demographic factors was 104.8 (SD 7.36). This group had completed a mean of 12.3 years' full time education (SD 4.01).

In addition, a group of 29 patients with a diagnosis of aMCI - that is, individuals with memory decline (both self reported and objectively measured), but an intact ability to perform activities of daily living, and an absence of dementia - was recruited (n=10 from Cardiff and n=19 from Bristol memory clinics). None was taking medication that would affect cognitive functioning. Exclusion criteria for both patient groups included a past history of serious head injury, stroke or other significant neurological or psychiatric condition. One aMCI patient was excluded from analysis because he completed only 4 trials of the motion task, and two because they responded to the motion task on the basis of rotational direction rather than which side had the moving stimulus (see "stimuli" below). The remaining 26 (15 male) were aged 67-90 (mean 77.7, SD 6.06) years, with MMSE scores ranging from 18 to 28 (mean 24.8, SD 1.99). Their mean premorbid IQ was estimated at 111.6 (SD 10.73) using the NART and 107.3 (SD 10.42) from demographic information, and a mean of 11.8 (SD 2.56) years' full time education had been completed.

The patient groups were compared with a group of 32 cognitively healthy older adults (16 male) recruited through contacts of the same memory clinics. Twenty five were from the Bristol memory clinic's older adults' volunteer database and had been confirmed as cognitively healthy by a full neuropsychological examination within the previous 12 months. The remaining seven were spouses of participating patients at the Cardiff memory clinic who had been judged as healthy by the recruiting clinician. The age range was 57 to 86 (mean 76.0, SD 7.23) years and MMSE scores were 25-30 (mean 27.8, SD 1.48). Mean IQ scores estimated using the NART were 118.6 (SD 6.54) and from demographic data, 116.0 (SD 6.90). This group had completed a mean of 12.5 (SD 3.23) years' full time education.

A further group of 32 healthy young participants (16 male) was recruited from the University of Bristol. These were aged 18-30 (mean 20.7, SD 2.74) years.

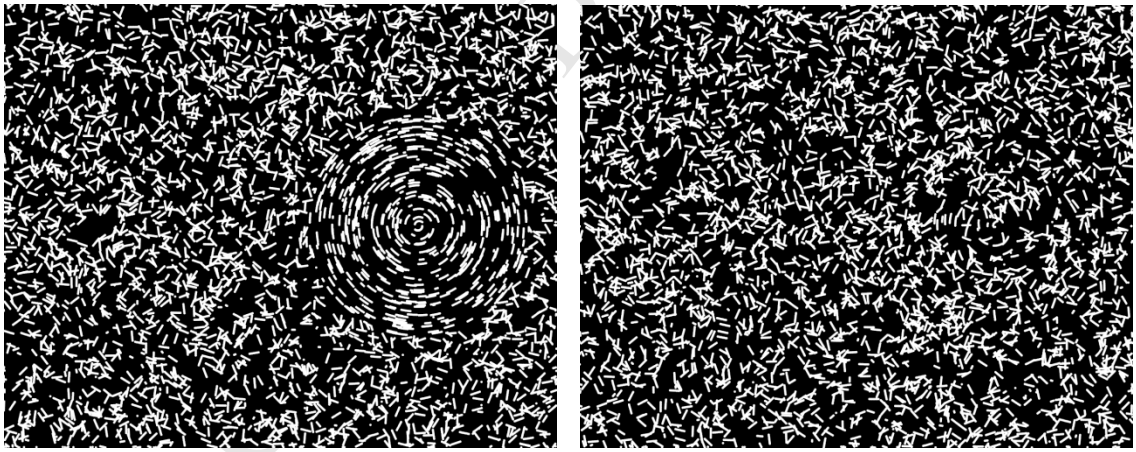
Participants completed this experiment in a test session of up to two hours, alongside a range of other research tasks reported elsewhere. All participants wore their usual spectacles or contact lenses, to correct their vision for the viewing distance required. A series of tests to assess older participants' corrected vision was included in their session, to confirm adequate visual capacity to complete the tasks. The AD group showed poorer corrected acuity than the healthy or MCI groups (scores on the Functional Acuity Contrast Test averaged 20/50.7 for the AD group, compared with 20/32.0 for the aMCI group and 20/31.4 for the healthy controls).

The study was conducted according to the principles in the Declaration of Helsinki. The study was approved by Frenchay (Bristol) and South East Wales (Cardiff) Research Ethics Committees, and all participants (including AD patients) gave written informed consent to their own participation. Only people with the capacity to consent were included in the study (in keeping with the requirements of the ethics committee). Assent from family or carers was not sought. Capacity was assessed by clinicians (AB and JH) with specialist expertise in this field and consistent with the requirements of the Mental Capacity Act.

2.2 Stimuli and tasks

Equivalent stimuli were used to measure static form coherence thresholds and rotational motion coherence thresholds. An example of those used for the form task is illustrated in Figure 1.

Figure 1: Examples of the form coherence stimuli, which also illustrate the pattern of dot trajectories in the motion stimuli.



a) 100% coherence **b) 20% coherence**

The participant completed a two-alternative forced choice task, reporting which side of the screen (left or right) showed a circular pattern (always present). For the initial few trials, coherence was 100% (Figure 1a) – that is, the target region contained only concentrically oriented arcs, and the circular pattern could be clearly seen by all participants, to familiarise the participant with the task. Coherence was then systematically varied according to the Psi staircase procedure (Kontsevich & Tyler, 1999), so that the circular pattern comprised fewer than 100% of the possible concentric arcs and was obscured by line segments of random orientation (e.g. Figure 1b). The remaining arcs within the target region, and all the arcs elsewhere on the screen, were randomly oriented with the same distribution of curvature as

the coherently oriented arcs. The global form display contained 3000 stationary arc segments, 11 min arc width x 60 min arc length.

The global motion task was visually similar but involved dots continuously appearing, moving and disappearing with trajectories equivalent to the line segments in figure 1 - that is, coherent dots moved in concentric circular paths, with the percentage of dots sharing this coherent motion varying from trial to trial. The display contained 3000 dots of diameter 16 min arc, moving at 5.9 deg/sec. Each dot had a lifetime of 8 frames (133 msec) after which it disappeared from the screen. Whether the coherent figure in the motion stimuli rotated clockwise or anticlockwise varied randomly from trial to trial, but participants were instructed to focus on the side, not the direction, of motion.

Stimuli were displayed in white on a black background on either a Toshiba Tecra M4, or a Dell Precision M4300, laptop computer viewed at a comfortable distance (approximately 50cm) in a dimly lit room. The display size was 38 x 19 deg arc and the diameter of the coherent figure was 15 deg. Responses were given verbally or by pointing, and were input by the experimenter. Stimuli were displayed until response, and response latency was not recorded.

For both tasks, coherence thresholds were estimated from 30 trials of the Psi staircase where possible. One participant in each older group completed less than this (one AD patient completed 18 trials of the form task; one MCI patient completed 20 motion trials and an older control completed 27 motion trials); these were included in the analysis. Each task was completed once only with order counterbalanced within sample group. Other activities often intervened between the two tasks reported here.

3. Results

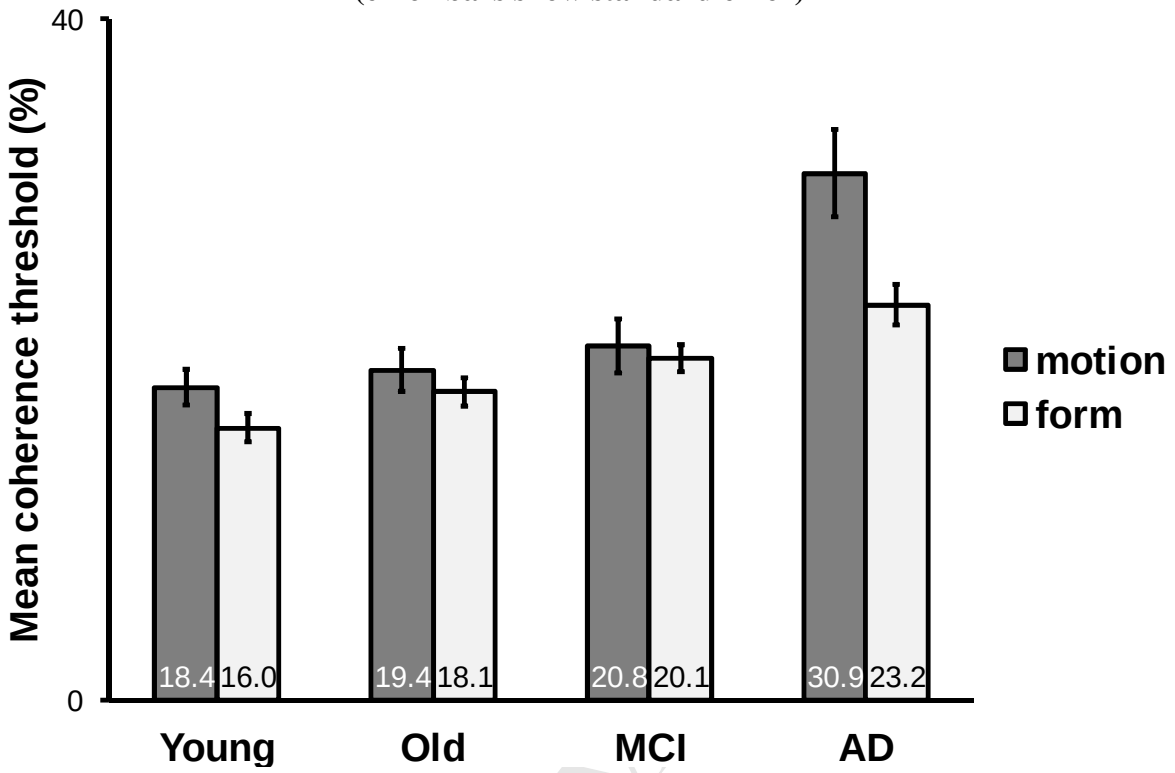
3.1 Group profiles

Independent samples t-tests, corrected for unequal variances using Levene's test where appropriate (*) and Bonferroni corrected for the use of multiple analyses (#), confirmed that the three older groups did not differ significantly in age or years' education. The chi-squared test showed no significant differences between the groups in gender composition. In keeping with their diagnoses, there were significant differences in terms of MMSE: the AD group scored significantly lower than the other groups (AD vs MCI: $t(48.7^*) = 3.82$, $p < 0.003^\#$; AD vs old controls: $t(40.2^*) = 9.13$, $p < 0.003^\#$), and the MCI group scored significantly lower than old controls ($t(54) = 6.28$, $p < 0.003^\#$).

The groups were also found to differ on IQ measures, and visual acuity as measured by the FACT. The AD group scored significantly more poorly on the FACT than either controls ($t(37.8^*) = -3.35$, $p = 0.006^\#$) or MCI patients ($t(36.6^*) = -3.28$, $p = 0.006^\#$), although controls and the MCI group did not differ. The older control group was recorded as being of significantly higher IQ than either patient group, whether using NART scores, demographic IQ or the higher of the two (NART scores for controls vs MCI group: $t(24.9^*) = 2.78$, $p = 0.060^\#$; controls vs AD group: $t(35.1^*) = 3.55$, $p = 0.003^\#$). The MCI and AD groups did not differ on the IQ measures. The influence of these differences in group profiles upon any differences in group coherence thresholds must therefore be considered.

3.2 Coherence thresholds

Figure 2: Mean coherence thresholds (error bars show standard error)



Mean form and motion coherence thresholds for each group are shown in Figure 2. A 2-factor mixed Analysis of Variance using the total data, with group (4) as an independent measure and task (2) as a repeated measure, showed significant main effects of group ($F(3, 114) = 15.1$, $p < 0.001$) and task ($F(1, 114) = 13.1$, $p < 0.001$), and, critically, a significant interaction between the two ($F(3, 114) = 4.03$, $p = 0.009$).

To investigate the nature of the interaction, repeated measures t-tests were used to assess task differences for each group separately. For young controls, old controls and aMCI patients, motion coherence thresholds did not differ significantly from form thresholds (young: $p = 0.072$; old: $p = 0.330$; aMCI: $p = 0.624$), although there is no intrinsic or theoretical reason why the thresholds for the two different tasks should be equal. In contrast, AD patients showed significantly higher motion than form thresholds ($t(27) = 3.02$, $p = 0.020$#).

Considering motion coherence thresholds alone, a univariate ANOVA on these data confirmed a main effect of group ($F(3, 114) = 11.0$, $p < 0.002$#). Independent samples t-tests showed no significant differences between young, healthy old and aMCI patients (young vs old: $p = 0.542$; old vs MCI: $p = 0.480$; young vs MCI: $p = 0.188$). However, motion thresholds for the AD group were markedly higher than for any other group (AD vs aMCI: $t(39.4^*) = -3.15$, $p = 0.018$#; AD vs old controls: $t(35.7^*) = -3.68$, $p = 0.006$#; AD vs young: $t(32.8^*) = -4.07$, $p < 0.006$#).

A univariate ANOVA on the form threshold data alone also showed a main effect of group ($F(3, 114) = 11.0$, $p < 0.002$#), but with more graduated differences between the groups. In independent t-tests, these did not reach significance between healthy young vs old ($p = 0.080$)

or old vs aMCI patients (p = 0.096), but were significant for young vs aMCI groups (t(56) = 3.46, p = 0.006#). Similarly, AD patients' form thresholds were higher than other groups', but the difference between AD and aMCI groups did not survive Bonferroni correction (AD vs aMCI: (t(46.3*) = -2.18, p = 0.204#; AD vs old controls: t(58) = -3.57, p = 0.006#; AD vs young: t(58) = -5.01, p < 0.006#).

3.3 Other factors

To clarify the possible influence of the poorer visual acuity in the AD group than the other older groups upon the coherence threshold patterns, we repeated the univariate ANOVAs but with the FACT score as a covariate. ANOVA using motion thresholds, with older group (3) as an independent measure and FACT score as a covariate, showed the significant effect of group (F(2,82) = 7.76, p = 0.002#) but no effect of FACT score (p = 0.717). Equivalent analysis using form thresholds showed the effect of group (F(2,82) = 5.48, p = 0.012#) but again no effect of FACT score (p = 0.601).

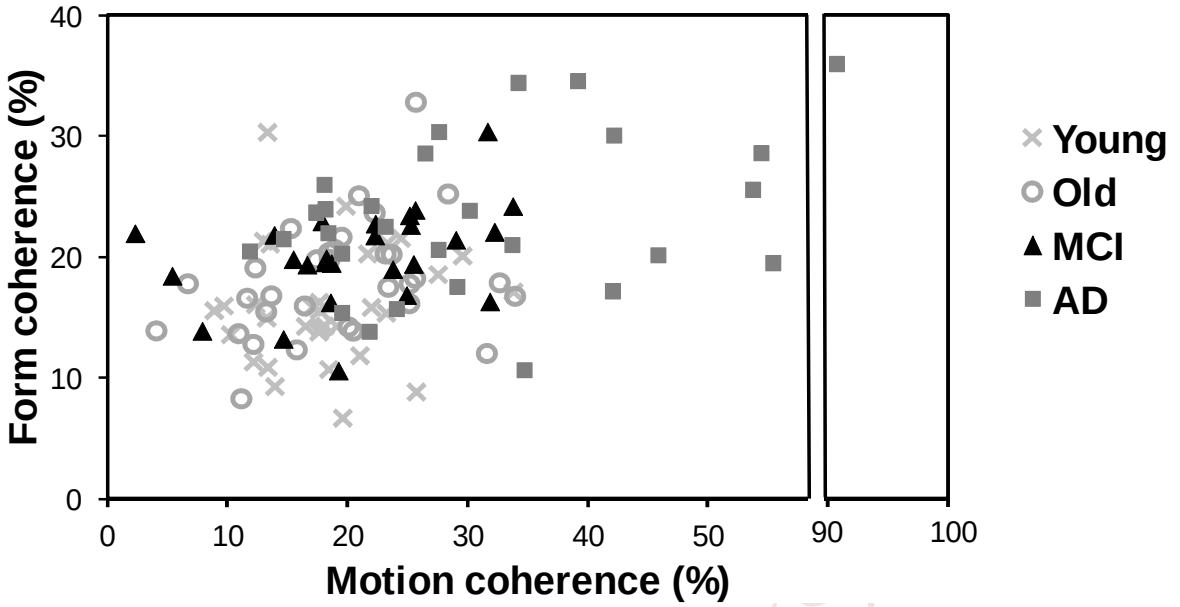
To clarify whether premorbid intelligence may affect the patterns, the same analysis was conducted replacing the FACT score with the NART IQ score as a covariate. The univariate ANOVA using motion thresholds maintained the significant effect of group (F(2, 66) = 5.81, p = 0.010#) but with no effect of NART score (p = 0.517). Using form thresholds, there was also an effect of group (F(2, 66) = 4.17, p = 0.040#) but no effect of NART (p = 0.807). Similarly, there was no significant effect of IQ using demographic measures.

Independent samples t-tests revealed no significant difference in either motion or form thresholds recorded for AD patients on cholinesterase drugs (ACh) compared with unmedicated (nACh) AD patients (mean thresholds for motion: ACh 30.3, nACh 33.7, p = 0.609; form: ACh 22.8, nACh 23.6, p = 0.755).

3.4 Correlations

Motion and form coherence thresholds inter-correlated across all groups (Pearson's R(118) = 0.455, p < 0.001; see Figure 3). Taking healthy young and older people together, no significant correlation was found between motion threshold and age (p = 0.771), although there was a marginally significant relationship between form threshold and age (R(62) = 0.247, p = 0.053). Among the patient groups, no significant Pearson's correlation was found between MMSE and either motion or form coherence thresholds (motion: p = 0.097; form: p = 0.329).

Figure 3: Coherence thresholds by individual



4. Discussion

We used a well-established methodology to measure thresholds for recognising coherent motion and static form in AD and aMCI patients, compared with older and younger healthy controls. In keeping with previous reports (e.g. Atkinson & Braddick, 2005), the stimuli which we used evoked coherence values which were largely equivalent for form and motion tasks in healthy adult participants: form thresholds did not differ from motion thresholds at a group level for either younger or older control groups, and the two measures intercorrelated with a high level of significance. For patients with aMCI, the patterns were very similar to those for the healthy participants. For AD patients, however, the data show a clear elevation of motion coherence thresholds specifically, both in comparison with their own form thresholds, and with motion thresholds for the other three sample groups.

Could any factors other than disease status explain these group differences in motion coherence thresholds? Two possibilities were visual acuity and premorbid IQ, given that both differed significantly between the older groups. In particular, the AD group had poorer corrected eyesight, as measured by the FACT, than either the MCI or older control groups, which exactly mirrors the pattern seen for the motion coherence thresholds. A relationship of poorer acuity to more marked dementia symptoms is already known (e.g. Cormack, Tovee & Ballard, 2000; Elyashiv, Shabtai & Belkin, 2014). However, since the FACT scores were unrelated to the motion thresholds when used as a covariate, visual acuity seems unlikely to be driving the motion perception differences here. Similarly, other studies have shown that neither motion nor form thresholds measured in this way are greatly affected by reduced acuity, and if anything blur impairs form perception more than motion (Braddick et al, 2007; Burton et al, 2015), so this would not explain the current results.

Measured intelligence also differed by group, but the pattern was different for IQ from that for motion coherence: AD and MCI groups had equally low mean IQ compared with the controls, not just the AD group, as might be expected if IQ and motion perception were related. Since IQ was also non-significant when used as a covariate with the motion thresholds, we assume that IQ did not contribute to the group differences in motion

perception. Other demographic factors were closely matched across the older groups and could not explain group performance differences.

4.1 Motion vs form compared

We conclude that our data show a specific deficit in global rotational motion processing in AD patients, which is not apparent in comparable form processing systems. Thus, motion processing deficits in AD do not reflect broad declines across global visual processing mechanisms. This reinforces previous reports suggesting more disruption to classic dorsal stream functioning than ventral stream in AD (Nguyen et al, 2003; Sartucci et al, 2010; Kubová et al, 2010), and explains why many more studies claim complex motion-related deficits than form-related deficits in these patients. The patterns reported here for AD are similar to those found in developmental disorders in childhood using the same methodology (Spencer et al, 2000; Atkinson et al, 2006), and they allow us to extend the concept of "dorsal stream vulnerability" (Braddick et al, 2003) into disorders of old age.

In addition, our data demonstrate equivalent performance across form and motion processing systems in healthy ageing and also aMCI. This suggests that although vulnerable, the ability to recognise coherent rotational motion specifically is diminished only by quite marked development of the disease process. Our data contrast with previous studies which emphasised exaggerated motion-related over form-related deficits in healthy older and MCI groups (Kuba et al, 2012; Lemos et al, 2012). However, these reported task-specific differences involved a temporal component, representing either delayed ERP latencies (Kuba et al, 2012) or a time-constrained task (Lemos et al, 2012), whereas ERP amplitudes or performance thresholds (more comparable to our measures) were more consistent by task. Changes in speed of processing in these older groups may affect subtleties of how moving, as opposed to static, stimuli are perceived – but our data show that such temporal changes may not simultaneously raise the threshold for identifying the presence of rotational motion at the stimulus speeds used here.

4.2 Motion processing in ageing, MCI and AD compared

Our data reinforce previous reports that AD involves performance deficits across a range of higher level complex motion tasks (e.g. Rizzo & Nawrot, 1998; Kim 2012), along with weaker activation of motion processing areas (Thiyagesh et al, 2009; Kavcic et al, 2006; Kubová et al, 2010), compared with older controls. Our results also support others' claims that performance at higher level motion processing is well maintained in healthy older compared with younger people, using rotational (Allen et al, 2010) or other complex motion stimuli (Atchley & Andersen 1998, Billino et al 2008). Importantly, we also show that the recognition of coherent rotational motion was not yet impaired across our aMCI patient group, although as discussed above, there may be underlying changes affecting subtle aspects of motion perception within this group. Such changes, as well as differences in MCI aetiology between samples, may have driven the altered activation and EEG responses to optic flow in MCI reported by Yamasaki et al (2012a and b). A key point is that there may be a qualitative step change in the ability to recognise coherent rotational motion as AD develops, but our MCI data suggest this is unlikely to occur early enough for tasks such as those used here to show potential for earlier diagnosis.

We also found the motion-specific impairment to be marked in some AD patients, but absent in others (see figure 3), irrespective of patients' functional abilities in other domains, since

motion thresholds were unrelated to MMSE. [Note that we did not include Posterior Cortical Atrophy (PCA) patients in the present study, so this could not explain the more extreme impairments found here. PCA is a relatively rare condition, closely linked to AD, which typically involves visuospatial and visuoperceptual impairments, often with underlying abnormalities in basic visual operations related to form and motion processing (see Crutch et al, 2012). PCA can lead to impaired global motion sensitivity, although the presentation is variable and in some PCA patients form coherence is more disrupted than motion coherence (Lehmann et al, 2011).]

Similar observations of inter-individual variability in motion deficits have been made by other authors (Tetewsky & Duffy, 1999, Fernandez et al 2007). It seems that while brain systems crucial to performing this motion recognition task may be particularly vulnerable to AD pathology, the heterogeneity of disease progression, and of patients' ability to tolerate pathology according to cognitive or brain reserve (Stern, 2009), means that these specific systems may nevertheless remain functional in many patients.

4.3 Form processing in ageing, MCI and AD compared

The form coherence data showed a rather different pattern. The correlational data hint at a slight increase in form coherence thresholds with increasing age, and group comparisons indicate further slight increases with deteriorating health status, reaching significance when comparing MCI patients with young controls, or AD patients with controls of either age group. Again, these patterns could not be explained by differences in visual acuity or IQ between the groups. This indicates a very gradual quantitative deterioration in the ability to recognise coherent form with ageing and dementia onset, but in contrast to motion processing, no qualitative step change.

Our data fit with reports of some age-related impairments at processing static form in AD (Kurylo et al, 2003; Uhlhaas et al, 2008), but contextualise these as much less dramatic than the comparable motion processing changes. These results are also compatible with reports of age-related deterioration in specific form-processing capabilities (e.g. Roudaia et al 2011, 2013; McKendrick et al, 2013), assuming that these studies were sensitive to more subtle changes than ours. The patterns here indicate that although brain circuits involved in form recognition tasks are subject to age- and disease-related decline, performance is generally well preserved. Thus, in addition to a postulated greater vulnerability of global than local visual circuitry to AD pathology (Beker et al, 2012), global motion-related cortical systems may be more vulnerable than the equivalent form systems. This would fit with evidence that neurofibrillary tangles distinctively target very specific brain regions (e.g. Lewis et al, 1987; Carlyle et al, 2014) and in particular the long-range connections between early visual areas and MT (Hof and Morrison, 1990). Possibly, too, form processing may be more readily maintained by the compensatory reorganisation of neural networks (see Kuai & Kourtzi, 2013; Mayhew & Kourtzi, 2013) than motion recognition.

5. Conclusions

The data reported here demonstrate that the ability to recognise coherent rotational motion is well maintained in healthy ageing and aMCI, but undergoes severe qualitative disruption in some patients with AD, unrelated to their overall level of functioning. In contrast, the ability to recognise coherent static form of equivalent difficulty seems to deteriorate gradually with increasing age and disease development, with no marked changes and with performance

reasonably well preserved in both aMCI and AD. This pattern reflects the much more prevalent reporting of motion- than form-processing declines in AD, but remains compatible with recent reports that subtle aspects of form recognition may be impaired in older groups.

These data allow us to conclude that, just as motion processing systems are differentially prone to disruption early in life, "dorsal stream vulnerability" also occurs in some AD patients. Although growing evidence leads us to question the extent to which dorsal and ventral processing streams are functionally or anatomically separate, the severe disruption to the ability to recognise motion, but not form, in many AD patients demonstrates clear differences in the brain systems involved in performing our two tasks. We speculate that such disruption to motion processing systems may result when targeted pathological deterioration in the motion-specific long-range connections of visual association cortex reaches a critical level.

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Highlights

Different trajectories of decline for global form and global motion processing in ageing, Mild Cognitive Impairment and Alzheimer's disease

1) Study uniquely compares healthy/MCI/AD groups using equivalent form/motion stimuli

2) Some AD patients show marked deficits in recognising motion coherence

3) The motion deficit here is specific to those with an AD, not an MCI, diagnosis

4) Motion processing deficits in AD significantly exceed the equivalent form deficits

5) Form processing also declines with ageing/AD, but more gradually than motion